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TRUSS-TYPE SUPPORT STRUCTURES FOR SLM

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Abstract

Support structures are critical in selective laser melting (SLM) of 3D metal additively manufactured components. Besides providing structural support, they serve as conduits for efficient heat dissipation. Support structures heavily influence the printability of a part as well as its physical and mechanical properties. Commonly used thin walled surface support structures are reliable, but are difficult to optimize, post-process, and often entrap a significant amount of powder. This paper presents the concept of truss-type surface support structures for SLM to address these challenges. The proposed structures are easy to optimize and provide better anchorage; further, they do not entrap powder, and are easy to remove. Experimental results demonstrate the effectiveness of these designs over commonly used support structures, paving a path towards optimal support structure design for SLM.

Introduction

Metal additive manufacturing has evolved to an exciting field in engineering, with applications in design and production of highly customized parts. The ability to generate near-net shaped products, that were otherwise impossible to manufacture earlier, has led to greater interest in the technology. Innovation in material science, design methodology and enabling technologies have equally contributed to the use and adaptation of additive manufacturing in product development [1, 2, 3, 4]. Despite advantages in additive manufacturing technologies, challenges exist. Almost all of the AM parts require post-processing for better physical and mechanical properties. These processes are comparatively very slow and require highly skilled technical manpower to operate the machines. Though AM processes claim to be able print parts to near net shape, designers need to be aware of the manufacturing processes and parameters to ensure a successful build.

Powder bed fusion (PBF) based metal additive technologies are widely used for their ability to generate high quality functional parts. Selective laser melting (SLM) is one of those

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processes, that uses 15μm - 45μm metal powders to print high precision parts. However, for any part to be printed on a SLM machine, the part needs to be welded on a build plate. Anchors or support structures are added in between the part and build plate in order to avoid any part damage during removal from build plate [5]. Also, downward facing surfaces with their normals inclined at or over a predefined angle (45°) with the direction of build cannot be printed. Support structures are needed to hold up these overhang surfaces to enable a successful part print in the powder bed.

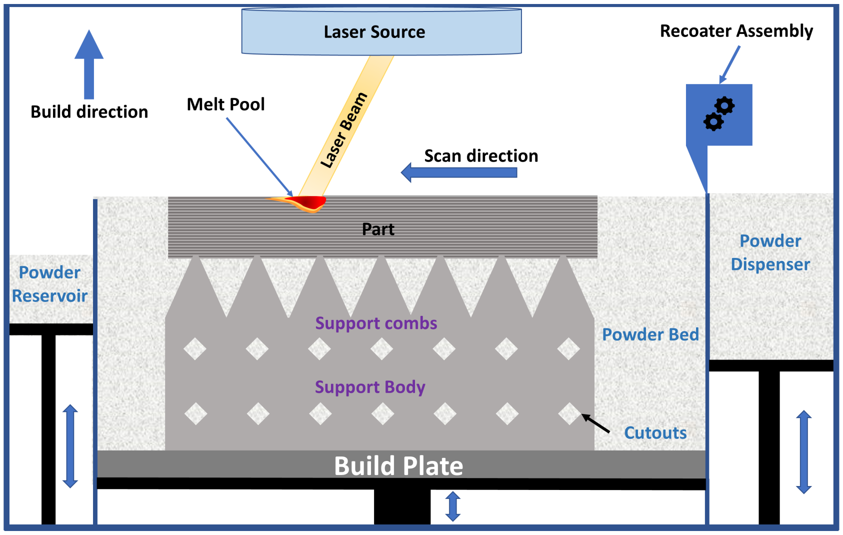


Figure 1: *Schematics of Part build in SLM*

A schematic of a part build in SLM with support structures, is shown in Figure 1. A support structure is composed of a support body and a support comb or tooth. Small cutouts are designed in the support body for easy removal of entraped powder. The support combs are penetrated into the parts to ensure better adherence of part to the support structure.

Unlike polymer based AM processes, where support structures counter the effect of gravity on these overhang surfaces, support structures in powder bed fusion based metal AM primarily act to swiftly transfer heat from a build layer to the build plate. Since the thermal conductivity of the metal powders is less than 10% compared to their solid counterparts [6, 7], solid printed metal support are required to act as paths for heat flow during printing. Insufficient support to any part in metal additive manufacturing can be detrimental to the print. As parts are built layer-wise, each layer has to be sufficiently supported to avoid layer distortion resulting from residual stresses. The inhomogenous nature of localized heat distribution at each layer with respect to space and time, results in residual thermal stresses build up on a part, leading to part distortion[8]. Also, insufficient attachment of support structures with build plate or the printed layers leads to recoater blade interference. This damages the recoater blades as well as the overall build space. Support structures influence the size, shape and morphology of different microstructural features in a printed part [9, 10, 11], making them critical components in powder bed metal additive manufacturing.

Support structures are printed using the same material as the part, leading to significant wastage of material, time and energy. These support structure require post-processing to remove them from the parts as well as the build plate, ultimately adding to the overall cost of the part during printing as well as post-processing. Thus, better strategies are required to carefully address these impending issues during design and manufacturing of support structures.

Well designed support structures for powder bed metal additive manufacturing process need to satisfy the following requirements,

1. Efficient heat transfer to the build plate
2. Adherence to part and build plate
3. Minimum material usage and print times
4. No powder entrapment
5. Ease of removal

This paper puts forward the idea of truss-type support structures which avoid powder entrapment and satisfies all requirement in terms of thermal management and structural integrity. Next section presents a brief survey of existing designs of support structures in use along with their merits and shortcomings. The new type of support structure is proposed in the following sections, with details about its construction and advantages. Conclusion along with some future scope of work are laid out at the end of the paper.

Existing Support Structure Designs

Support structures in general can be classified to two different types based on their geometric definition as discussed below. The support structures defined for printing on SLM also guide their printing processes, functionality, and applications.

1. **Solid-based support structures:** These types of support structures have a volume definition. They are watertight bodies and have an explicit interior, meaning each member has a defined cross-section. The infill of each members, thus require multiple laser scans per layer to print. Often, these types of support structures have large file sizes. The cone-type design shown in Figure 2 is a typical solid-based support structure design. Cloots et.al [12] have used solid lattice-type support structures to minimize part distortion whereas Cheng and To [13] used lattice-based support structures to minimize the support volume and residual stresses. Cheng et.al [14] used graded lattices generated through topology optimization to design support structures to prevent residual stresses induced failures. Gan and Wong [15] designed Y-type, inverted Y (IY) and Pin-type support structures for use in SLM. Cooper et.al [16] proposed contact less support structures. A small gap is created between part and solid support structures, that acts as a heat sink. The top face of support structure mimics the surface requiring support and is offset by a small distance below the surface. One of the biggest drawbacks of these solid-based support structures proposed by researchers is

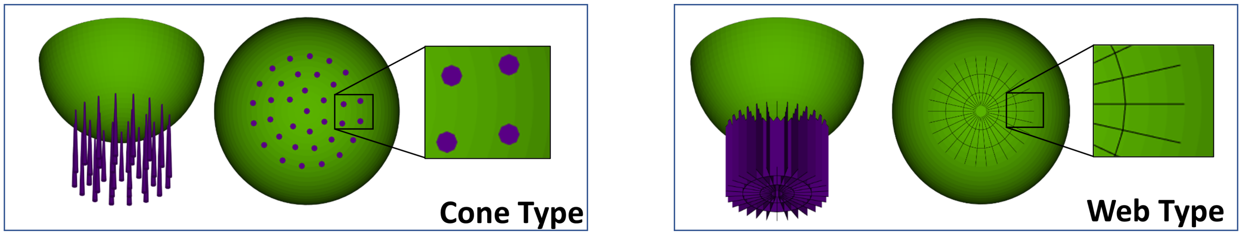


Figure 2: *Examples of Solid (R) and Surface(L)-based support structures*

poor manufacturability. Combs aren't explicitly defined leading to heavy metal dross at the interface of support structure and part.

2. **Surface-based support structures:** These types of support structures do not have a cross-section. The members have zero-thickness, computationally resembling shells, plates or trusses with no thicknesses. The thickness to these structures are implicitly applied by the melt pool during single laser pass per layer, which are dependent on the printing parameters. Also, since the members are printed on a single laser pass, the printing process is faster compared to solid-based support structures. These support structures are easier to remove and often have smaller file sizes. The web-type design shown in Figure 2 is a typical surface-based support structure design. Block-type support structure shown in Figure 3, is a surface-based design and available in most of the commercial build preparation softwares. The walled structure surrounding the support volume in this type of design prevents curling up of edges on parts. Though perforations are provided in these walls, a significant amount of powder gets entrapped within these walled structures, leading to valuable material wastage. These walled designs make them difficult to remove from the build.

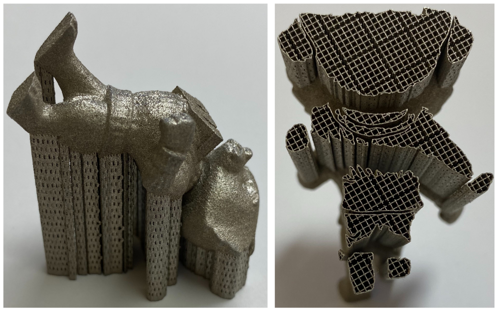


Figure 3: *Wisconsin Bucky printed with surface-based block-type support structure*

Krol et.al [17] used finite element-based models to obtain fractal variations of block-type support structures. Experimental verification on the success of these support structures have not been provided. Strano et.al[18] and Hussein et.al[19] have used triply periodic minimal surface lattices as support structures. The size and shape of these periodic structures were controlled through geometric parameters, however, some print samples failed due to very small thickness of support structures or large unsupported lengths.

The thin walled type support structure are difficult to analyze, whereas the solid beam type supports have very poor part manufacturability. The existing support structures are non-optimal in terms of material usage as well as thermal management. Thus, there is a need for better designs of support structures, that leverages the benefits of both types of designs so as to prevent print failures and, save material, time and effort during printing as well as post-processing.

Truss-type support structures (TSS)

This study proposes truss-type support structures for use in SLM. These are open structures that avoid any powder entrapment and are easier to analyze as well as optimize. Both solid-based and surface-based supports can be generated with the choice of cross-section shape for each of the truss members. The truss members make fewer contact with the build plate as well as the part, compared to the walled designs, making them much easier to remove during post-processing. Different choices of cross-sections for the truss members are explored and analyzed to demonstrate the suitability of their usage as support structures. The details of truss-type support structures (TSS) are discussed below.

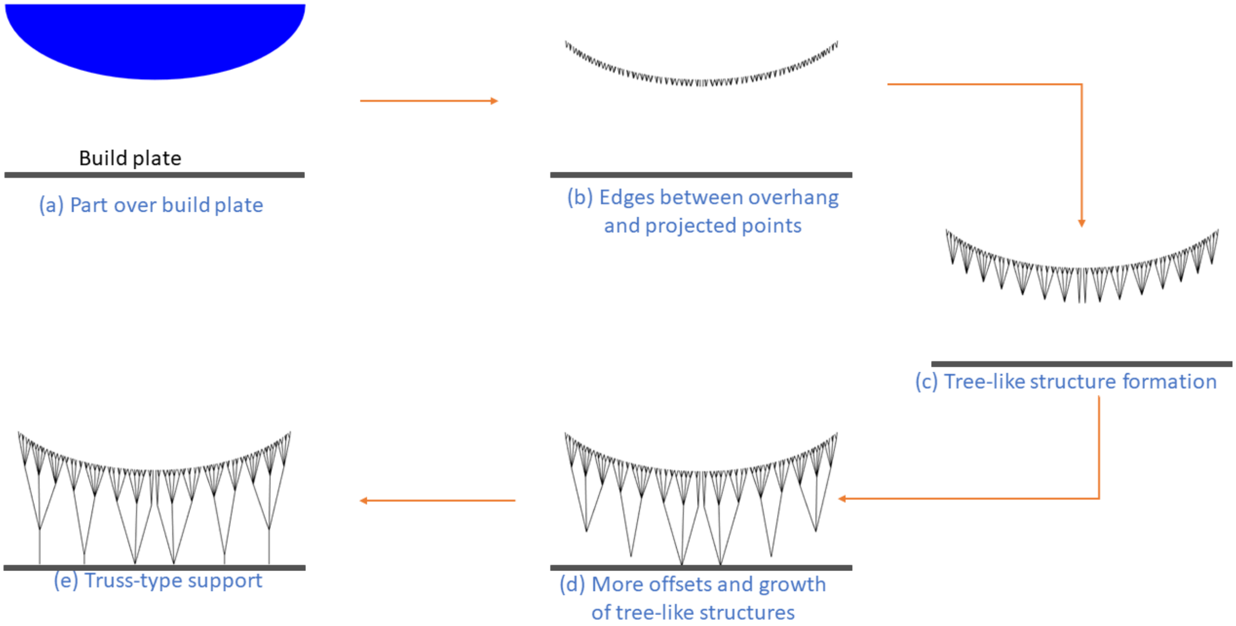
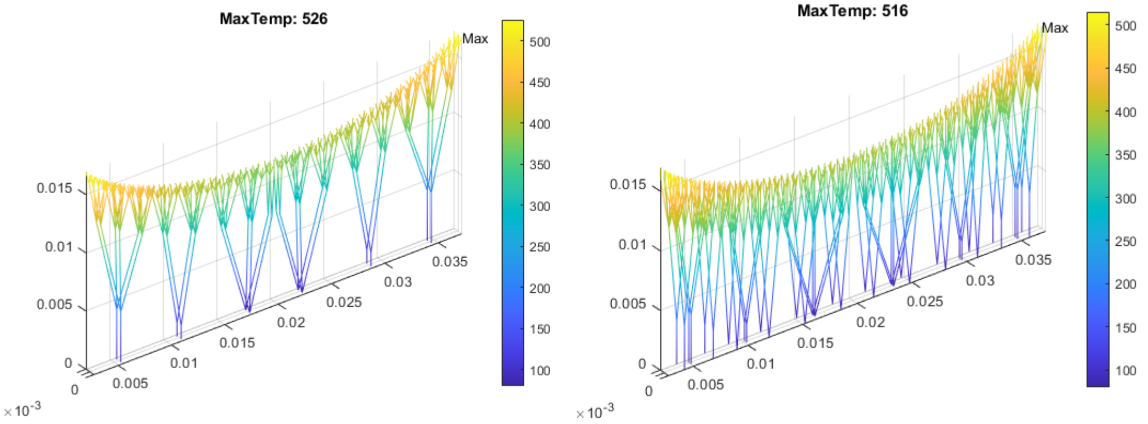


Figure 4: *Algorithm for Truss-type support structures*

For any part with a given build orientation and placement over the build plate, an overhang surface is the collections of surface triangles whose normals are inclined at or over 45° with the build direction. The vertices of these triangles are projected downwards by offsetting them in the negative build direction. Connectivity among the overhang vertices and the projected point is established based on the inclination of lines connecting a projected point to all overhang vertices. Only those connections that conform to the maximum overhang angle of 45° with build direction are saved as truss members. This ensures each connected member to be self-supported. Multiple unsupported points can be supported by a single point, generating a tree-like structure. Once all overhang vertices are supported by projected points, these set of projected points are considered as overhang vertices. The process of projection and edge creation repeats until the projected points reach the build plate. Collection of all such tree structures gives rise to a support truss. Figure 4 shows the algorithm for generating truss-type support for half ellipse part placed over the build plate with a defined orientation and placement.

One of the advantages of using truss-type design is the ease of thermal analysis of support structures. A 2-noded truss element-based static thermal finite element analysis (FEA) is performed on the support structure with constant heat flux applied on the top nodes while dirichlet boundary on the truss nodes attached to the build plate. Each truss member is assigned an area based on the total support material volume to be used in printing the part. Figure 5a shows results of thermal analysis of support structure with maximum temperature on the truss members supporting the free edges of an unsupported patch.

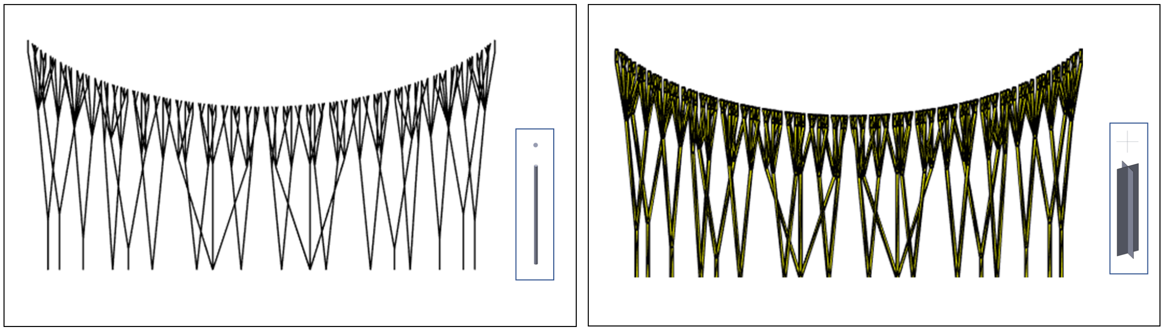


(a) *Thermal analysis on TSS without skirts* (b) *Thermal analysis on TSS with skirts*

Figure 5: *3D Thermal analysis of truss-type support structures*

As large amount of heat gets accumulated on the top layer due to insufficient support and slower heat conduction to the build plate, the free edges of an unsupported surface patch, tend to expand. However, as the layer begins cooling, the already built underlying layers constrain the expansion, leading to shrinkage and curling up of the new layer [20]. This effect causes part warpage on cooling. To alleviate this issue of maximum temperature over the free edges, more supporting members are required. Thus, two different support trusses are generated, one with the nodes from free edges of unsupported patch, called skirt truss and the other with rest of the unsupported nodes, called the interior truss. These two trusses are combined to form the truss-type support structures (TSS). Results of static thermal FEA on the combined truss-type support structure is shown in Figure 5b. The point of maximum temperature shifts to the interior of the unsupported patch along with some reduction in its magnitude.

Once the support structures are analysed, the line members of trusses need to be triangulated to generate an .STL file for printing. As discussed earlier, there can be two different choices of support structures based on their geometric construction. A solid-based TSS has circular cross-section for each of the members. The cylindrical surface of the members are divided into multiple sections to create rectangles, which are then subdivided to create triangles to be saved as .STL files as shown in Figure 6a. For the surface-based TSS, each line member is extruded along directions normal to the line orientation. The extruded points are connected to create rectangles, which are then subdivided into triangles. These triangles along with their connectivity information can be saved as .STL file to be used in SLM. A four-finned design of surface-based TSS is shown in Figure 6b. The fins on these support structures have no thickness, meaning the thickness to the members are implied by the solidified melt pool as laser traverses its path during printing.

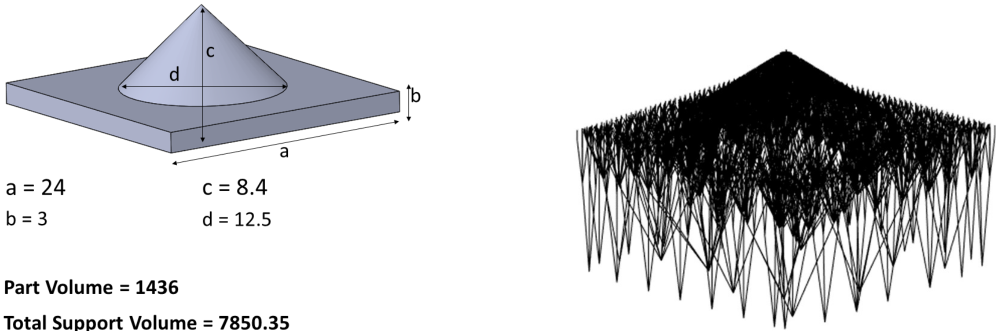


(a) *Solid-based TSS, with circular cross-section*

(b) *Surface-based TSS, with 4-finned cross-section*

Figure 6: *Types of TSS based on geometric construction*

A modified hat specimen was chosen for validating the printability of part with TSS. Part details have been presented in Figure 7a along with the corresponding truss-type support structures in Figure 7b.



(a) *Specimen details (in mm)*

(b) *TSS for modified hat specimen*

Figure 7: *Modified Hat specimen with TSS*

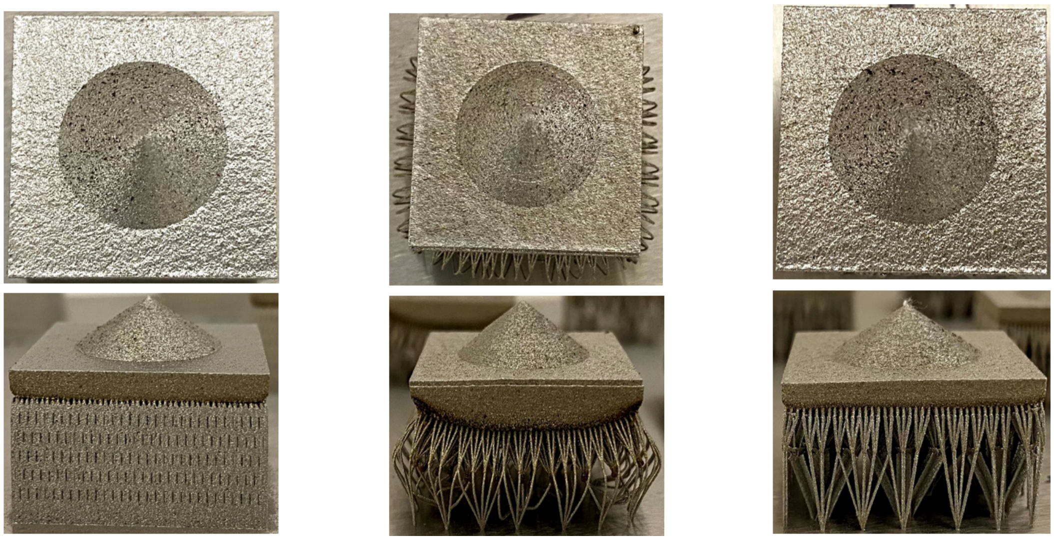
The specimens were printed on an EOS-M290 machine in SS-316L powder, with the following printing parameters,

Part

- Layer Thickness: 20μm
- Laser Power: 195 W
- Laser Scan Speed: 1083 mm/s
- Hatch Spacing: 90μm

Support Structures

- Layer Thickness: 40μm
- Laser Power: 100 W
- Laser Scan Speed: 675 mm/s
- Minimum height: 12mm



(a) *Block-type support with 20.02% support volume* (b) *Solid-based TSS with 15% support volume* (c) *Surface-based support with 16.14% support volume*

Figure 8: *Results of manufacturing trials*

The same specimen was printed using a block-type support generated from Materialize Magics®. Results from manufacturing trials have been presented in Figure 8. The control specimen printed with a block-type support (see Figure 8a) used 20.02% support volume to print whereas, the surface-based TSS (see Figure8c) used only 16.14% volume fraction of the total support volume to print the part. Besides using close to 20% less material to print a part, the four-finned surface-based truss-type support do not entrap any unmelted powder within them, thereby reducing powder wastage.

The modified hat specimen printed with solid-based TSS buckled under thermal load leading to a print failure as seen in Figure 8b. Buckling failure of the solid TSS is attributed to their smaller area moment of inertial. For the same truss topology, the four-finned design of the surface-based TSS has over 5 times the buckling resistance as compared to the one for the solid cylindrical TSS, making them the preferred choice.

These truss-type support structures have fewer contacts with the build plate compared to the block support. Also, surface based truss members, owing to their thin cross-sections, can easily be broken off the build plate with a minimal twisting force and do not need costlier wire EDM removal. Thus, the post-processing of parts is significantly cheaper in terms of time, cost and efforts.

Conclusion

A new type of surface-based support structure was designed and successfully put to use for printing samples in SLM. This type of support structures use less material to print, avoid powder entrapment, and are lighter and easier to remove, thereby saving material, and cost for printing as well as post-processing. Finite element analysis of the support structures indicated the need for extra enforcement along the free edges of the unsupported patch to reduce warpage. Addition of skirts along the free edges reduced the maximum temperature and provided better thermal management. Also, results from manufacturing trials showed the suitability of 4-finned surface-based designs over the cylindrical solid-based truss-type supports due to their higher buckling resistance.

The preliminary results presented for the use of finite element engine helped in creating better support structure topology for thermal management. This engine can further be used to understand the thermal history of any part build. Results from such analyses can help in predicting part distortions due to thermal and structural stresses, and implement strategies to avoid failures induced by such stresses.

Considering the amount of metal powder used for printing support structures, and unmelted powder entrapped within the supports for a block type design, the proposed truss-type supports used only around 20% material to print the same part. Thus, significant amount of material powder saving has been made in comparison to the commonly used block type supports. However, the minimum material volume required for these supports are still referenced from commercial softwares. A metric to determine adequate material required for a successful part build will also be investigated using the FEA engine. These ideas on thermal management within a part build will be addressed in subsequent publications.

The next step would be to optimize the support structure based on thermal analysis. An optimizer that uses the existing 3D FEA engine will be created to optimize the truss-type supports for minimal material usage and faster print times. More testing and validation through experimentation will be performed to ensure higher reliability of these methods.

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